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# DEVELOPMENT OF AN EXPERIMENTAL SILICON CARBIDE BACKWARD DIODE OPERABLE TO 1000° K

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## ABSTRACT

Silicon carbide backward diodes which operate between 77°K and 1000°K have been developed. Figures of merit ($\gamma \sqrt{R}$) of 19,300, 3,960, and 15 at 12.5 MHz, 50 MHz and 8.8 GHz, respectively, have been measured with detector areas on the order of $10^{-5}$ $cm^2$. These results are compatible with a prior analysis which predicts an upper frequency limit of between 0.1 and 1.0 GHz for SiC backward diodes.

# DEVELOPMENT OF AN EXPERIMENTAL SILICON CARBIDE BACKWARD DIODE OPERABLE TO 1000°K

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## SUMMARY

Silicon carbide backward diodes which operate between 77°K and 1000°K have been developed. Figures of merit ($\gamma \sqrt{R}$) of 19,300, 3,960, and 15 at 12.5 MHz, 50 MHz and 8.8 GHz, respectively, have been measured with detector areas on the order of $10^{-5}$ $cm^2$. These results are compatible with a prior analysis which predicts an upper frequency limit of between 0.1 and 1.0 GHz for SiC backward diodes.

## INTRODUCTION

The development of experimental silicon carbide backward diodes operable from cryogenic temperatures to about 1000°K is reported. P-type, $\alpha$-silicon-carbide doped to a level between $10^{20}$ and $10^{21}$ $cm^{-3}$ with aluminum is used as a starting material. The doping level has not been determined with any accuracy, but its uniformity is evidenced by the very even coloring of the material and by the reproducibility of the diodes.

## JUNCTION FORMATION AND PACKAGING

The junctions are formed by a modified version of the techniques of Rutz (ref. 1) and Hall (ref. 2). A SiC chip is first fused in vacuum to a 5-mil thick tungsten heater strip by passing current through the strip until at about 1800°C a tungsten carbide layer grows to provide an intimate thermal bond between the heater strip and the chip resting on it. The chip is next heated with a fragment of Si on top to about 2100 C in a nitrogen atmosphere. Full temperature is maintained for 5 seconds, and the sample is then allowed to cool quickly (< 5 sec) to room temperature. The Si when molten dissolves a small amount of SiC from the chip and absorbs nitrogen from its surroundings. Upon cooling, the SiC which recrystallizes from the Si contains enough nitrogen to make it degenerate n-type, thus forming the p-n junction.

Neither surface preparation of the SiC nor the type of Si used seems to affect the characteristics of the diodes fabricated. Polished, etched, and as-grown surfaces all yield the same results.

N-type (10 ohm-cm) and p-type (1000 ohm-cm) Si have been used with no apparent differences in the resulting diodes.

Following junction formation, the W heater strip is etched electrolytically in KOH to remove the diodes which are protected with photo-resist. An Au-Ta alloy is used to make an ohmic bond between the diode and the pedestal of a varactor package.

Choice of lead material to complete the package presented a considerable problem since, for high-temperature operation, a high eutectic temperature was required, while the mismatch of thermal expansion coefficients must be kept small enough to assure the mechanical integrity of the bond. These requirements were reconciled by the use of Cu-plated Mo wire. The wire is brought into contact with the Si dot (typically 50μm in diameter), and the device heated until, at about 800°C, Cu-Si bonding is observed. The limited amount of Cu available alloys with only a portion of the Si dot leaving the thermally durable Si-SiC bond intact. Diodes packaged in this way have withstood exposure to a temperature range from liquid helium to 1000°K.

The use of conventional SiC etches for reduction of junction areas on diodes packaged in this way proved unsuccessful. The materials used in the packaging, particularly the Si-Cu-Mo lead, quickly deteriorated when exposed to the etches.

Tungsten leads alloyed directly to the Si dot at about 1400°C were found to resist attack by a conventional HF-alcohol electrolytic etch. Junctions with such leads attached were reduced in diameter to a few μm using this etch with little or no change in the shape of their I-V characteristics. This type of lead was found to separate from the junction, however, when exposed to temperatures above 200°C. In packaging, it has not be possible to satisfy simultaneously the requirements of chemical resistance to etch and mechanical stability over a wide temperature for which data are subsequently presented.

## DATA AND INTERPRETATION

I-V characteristics of a typical diode at temperatures of 77°K, 300°K, and 600°K are shown in Figure 1. At room temperature, a slight tunneling hump is clearly evident, and the knee of the diffusion current is at about 2 volts. An anomaly shared with Rutz's Esaki diodes is the low conductance of the forward bias curve close to the origin of the I-V characteristic. This effect is not observed at temperatures above about 150°C. While this peculiarity remains unexplained, it is interesting to note that measurements by van Daal et al. (ref. 3) on p-type SiC indicate that at about this same temperature the conduction mechanism changes in such a way that polar scattering of charge carriers by optical phonons becomes predominant.

In Figure 2, I-V characteristics of a second diode are shown at 300°K, 700°K, and 1000°K. What appears to be an increase in the series resistance of the diode in the 1000°K characteristic is an indication of the failure of the Si-Cu-Mo lead which occurs at about this temperature.

The characteristics are quite well reproducible. In only one case out of several hundred was negative resistance observed at room temperature or below. The uniformity of our results may be related to the very reproducible heating conditions possible with our fabrication technique.

Probably the most important application of backward diodes in Si, Ge, and InAs is in microwave detection and mixing. The optimization of such device functions requires materials with particular electronic properties, specifically, small bandgap and low effective carrier mass. While SiC with its wide bandgap (~ 2.6 eV) and large effective mass (> 1.0) does not promise very high-frequency operation, Hopkins' analysis (ref. 4) indicates an upper limit in frequency of between 0.1 and 1.0 GHz. The preliminary room-temperature detection performance data shown in Table I tend to substantiate this prediction. Detection performance degrades by a factor of about 5 between 12.5 and 50 MHz and deteriorates considerably at 8.8 GHz. The X-band detection data, which yield tangential sensitiveties 20 to 30 dBm below commercial backward diodes, should be upgraded somewhat due to the fact that the SiC diodes tested had junction areas about 50 times as large as those of commercial diodes.

TABLE I

ROOM TEMPERATURE DETECTION PERFORMANCE OF SiC BACKWARD DIODE AT THREE FREQUENCIES

| Frequency | Voltage Sensitivity, $\gamma$ (mV/mW) | Figure of Merit, $\gamma\sqrt{R}$ (a) |
|---|---|---|
| 12.5 MHz | 585 | 19,300 |
| 50.0 MHz | 110 | 3,960 |
| 8.8 GHz | 0.5 | 15 |

(a) R = video resistance, typically 1000 Ω

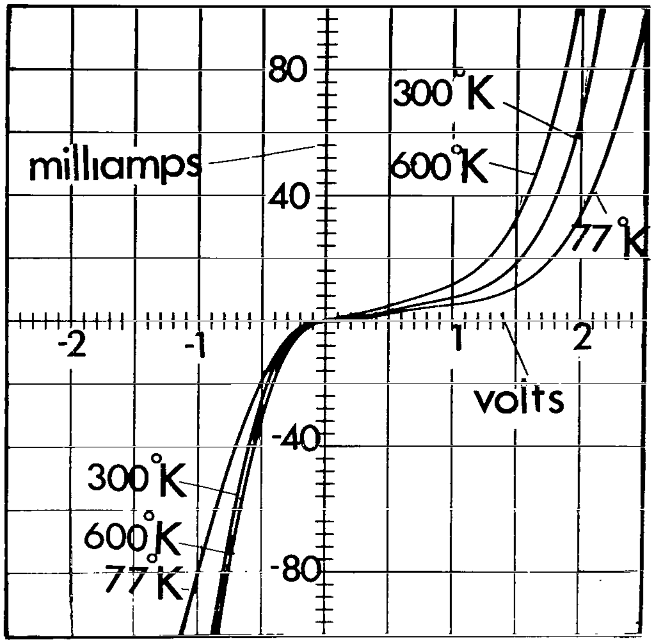


Figure 1.- I-V characteristics of SiC backward diode at 77°K, 300°K and 600°K.

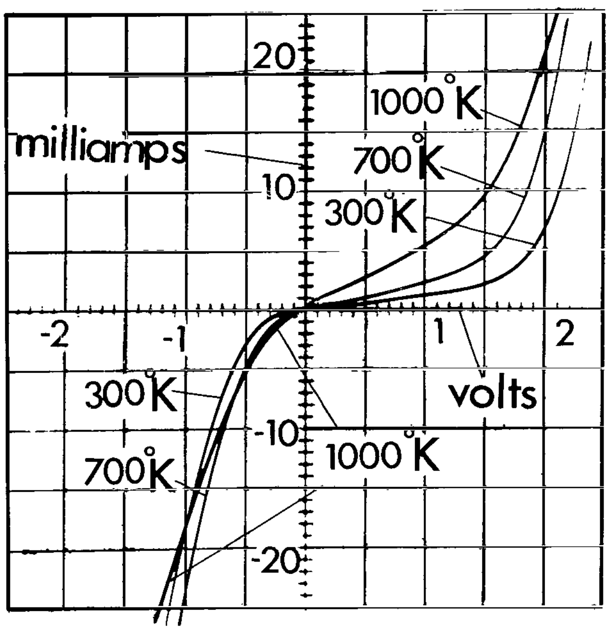


Figure 2.- I-V characteristics of SiC backward diode at 300°K, 700°K and 1000°K.

## CONCLUSION

It is apparent, however, that at present the high-temperature capability is the paramount feature to confer some degree of practicality upon the new device. Qualitative tests in which these diodes were operated as detectors at 12.5 MHz up to 1000°K have indicated a decrease by a factor of about 3 in the voltage sensitivity at 1000°K as compared to room temperature.

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Electronics Research Center
Cambridge, Massachusetts, November 1968
125-21-03-11-25

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